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THE USE OF REMOTELY SENSED DATA AS A TOOL IN URBAN HEAT ISLAND INVESTIGATIONS: AN OVERVIEW

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The Use of Remotely Sensed Data as a Tool in Urban Heat Island Investigations: An Overview

ABSTRACT

Remotely sensed data contributes an important tool to areawide, cost-effective studies of urban heat island phenomena. This paper provides an overview of its use dating from the first satellite thermal images of urban heat signatures in the early 1970's, and briefly examines the range of previous uses of remotely sensed data in urban studies, including identification and analysis of heat island effects, modeling of energy budgets, attempts to analyze and classify the urban landscape, and temporal analyses. The intent is not to provide an exhaustive review but rather to describe research trends and patterns. In addition the paper lists and compares those sensing devices that have seen significant use in urban studies and briefly discusses potential strengths and weaknesses of remotely sensed data for use in urban analyses. Three annotated bibliographies, divided by subject, are included.

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INTRODUCTION

Studies of urban heat island phenomena are currently undergoing a shift in emphasis on two fronts. Analytical studies are moving toward finer resolutions in response to a growing body of evidence (eg. Pease et al., 1976; Pease and Nichols, 1976; Hoyano, 1984; Honjo and Takakura, 1986) that urban energy budgets vary significantly on local (10 m - 100 m) spatial scales. At the same time, attention is beginning to focus on mitigation efforts designed to make use of the present state of knowledge of heat island phenomena (eg. Beckröge, 1988; Fezer, 1990). The Heat Island Project at Lawrence Berkeley Laboratory now actively supports the use of the simpler and more cost-effective mitigation strategies, especially raising urban albedos and increasing urban tree populations; significant savings in energy are possible, along with other benefits (Akbari et al., 1990; for an overview see Garbesi et al., 1989).

Both of these new emphases require high-resolution data sets designed specifically to characterize those aspects of urban regions (see further Oke, 1989) that bear on the energy fluxes involved in heat island creation and mitigation[1]. Remote sensing is a unique element among the available tools for creating such data sets in that it provides comprehensive synoptic coverage of an entire area in a data format that is both easily manipulable and intuitively comprehensible. This paper reviews the past uses of remotely sensed data in urban heat island studies and attempts to characterize its potential in light of past experience and current trends in instrument design and analytical technique.

This paper represents one part of the first-year phase of a larger study whose purpose is to demonstrate appropriate use of remotely-sensed data in routine assessment of those aspects of urban landscapes that contribute to the creation of heat islands. These include straightforward variables such as apparent albedo, the type and density of vegetation and directly assessed surface temperature, as well as quantified geometric aspects of the urban fabric and spectral indices corresponding to particular landscape elements. The goal of the present paper is to explore methodologies pertinent to producing the required physical characterizations of cities[2].

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[1]This study and most others consider heat islands in negative terms: urban heat islands detract from human comfort in summer, and add to cooling costs and thus overall energy consumption with attendant CO_2 and other pollutant release. Heat islands in winter can be beneficial in that they add to human comfort and decrease heating costs — especially when insulation values and other thermal efficiencies are high, so that the major causative effects are lowered albedo, limited skyview and diminished advection. However, the inherent difference in energy efficiency between heating and cooling technologies means that urban heat islands are a net liability except in very cold climates.

[2]A following paper will particularly emphasize identifying locales within two sample California cities where heat island mitigation stratagems that are currently available can be cost-effective. An eventual goal must be to determine the most effective methods of communicating results, and to reduce such information into a readily comprehensible map form for ready reference by governmental planning bodies and others. This phase, presently under way, analyzes the cities of Fresno and Sacramento as pilot locales, studying patterns within those cities that relate to heat island generation, and determining possible mitigation strategies.

The Urban Heat Island and the Urban Fabric

Cities form complex patterns of structures and intervening open spaces both vegetated and bare, paved and unpaved. We refer to the amalgam of these constituent elements as the *urban fabric*. In some places the urban fabric consists of single-story residences well-spaced among wide lawns and tree-lined avenues; in other places it might be formed of multistory buildings separated only by the narrow canyons of alleys and streets, or of large low commercial buildings separated by extensive parking lots. Each of these, with its myriad of architectural and landscaping details, has specific attributes that determine how energy is absorbed or reflected, stored or dispersed. In turn, the ratios among those energy fluxes define the pattern of air temperatures that, when higher than equivalent temperatures in surrounding countryside, we refer to as the urban heat island.

Those intent on studying the urban fabric face a challenging paradox. Whereas the urban network of streets and public access ways seems to provide unusual freedom to travel to any part of the landscape, in fact access is tightly limited due mainly to the very large number of small properties, each owned or managed separately, many of them fenced or otherwise obscured from public view. To obtain permission and then to access even a small fraction of the landscape other than public rights of way requires considerable investment in time and effort.

Remote sensing provides a uniquely cost-effective means of gathering data from all portions of a landscape simultaneously, in something like a map view. For these reasons, urban planners and others have long relied on aerial photography for many of their needs. Besides traditional aerial photography (including infrared photography), remotely sensed data can include digital images of various spatial and spectral resolutions, utilizing wavelengths from the ultraviolet through the thermal infrared, obtained with state of the art scanning imagers mounted on low-flying aircraft, high-flying aircraft or satellite platforms.

Digital imagery obtained from scanning imagers greatly extends the information available to the investigator. Temperatures of objects and of the ground surface can be assessed directly. Apparent narrow-band reflectivities can be calculated, and from these albedo (reflectivity across the entire solar spectrum) can be estimated. The heterogeneity of the urban fabric precludes use of many remote sensing algorithms developed for agricultural studies in which crops and soils present a uniform fabric, but at least the density of healthy, transpiring vegetation can be assessed even against typically heterogeneous urban backgrounds. Sophisticated statistical approaches show promise for analyzing more subtle aspects of urban surfaces and fabrics.

Imagery from satellites is ubiquitously available, and, if subsidized, may be inexpensive. However, spatial resolution on the ground tends to be marginal for many urban studies. Also, satellites of the applicable types follow *sun-synchronous orbits*, that is, they orbit the earth in 24 hours. Thus while images of any given locale may be generated each day or once each number of days, the nature of such orbits dictates that they will only be generated at one particular time of day, which is determined by the satellite's orbit (certain satellites also collect limited data on the night side of the orbit: those images will similarly always be generated at the same time of night). Sensors mounted on aircraft, in contrast, can generate images at any time, from a range of altitudes, at whatever ground resolution the investigator requires and the equipment allows — but flight time and sensors are both costly.

Previous and Potential Work

Any line of research involving remote sensing must include in an assessment of research trends a parallel assessment of trends in the state of remote sensing technology. Evolution of sensing instruments, of analytical hardware and software, and of information-extraction approaches all proceed very rapidly. Work difficult to perform one year can become trivial the next using an appropriate new tool; worse, effort can be wasted if superior novel data sources or analytical approaches are ignored. For these reasons, this paper will review in context: that is, it will examine previous uses of remotely sensed data in heat island studies but will also review recent advances in remote sensing. The intent is to provide a useful contextual frame.

An initial comparison of common thermal data sources will help to clarify later discussion (also see Table 1). Routine civilian use of thermal satellite sensors started about 1970 when a Scanning Radiometer (SR) with a 10.2-12.5 μm thermal band and a ground resolution of 7.4 km was orbited on an ITOS weather satellite (Improved TIROS Operational Satellite, TIROS standing for Television InfraRed Observing Satellite); these were precursors to later NOAA (National Oceanic and Atmospheric Administration) satellites, which provide data for operational meteorological analysis. On the NOAA satellites the SR was replaced by the Very High Resolution Radiometer (VHRR)[3] whose thermal band (10.5-12.5 μm) had a ground resolution of 1 km; the data was still analog, and coverage was once each day and night. The Advanced Very High Resolution Radiometer (AVHRR) was introduced on the TIROS/NOAA fleet in 1978. One (10.5-11.5 μm) or two (10.3-11.3 and 11.5-12.5 μm) thermal bands have had ground resolutions of 1.1 km and improved radiance resolution, yielding data in 10-bit digital form. Coverage times have varied by satellite; the operational ideal is to provide coverage from successive satellites at three-hour intervals.

As novel uses for thermal image data were discovered, several experimental sensors were launched. The most common source used for urban heat island studies has been the Heat Capacity Mapping Radiometer (HCMR), launched on the Heat Capacity Mapping Mission (HCMM) in 1978. The HCMR thermal band (10.5-12.5 μm) had a ground resolution of 600 m. Coverage was 0130 and 1430 local solar time (LST). A shortwave band (0.5-1.1 μm) designed to aid in registration and to provide albedo information must be used with caution since it responded to green vegetation very strongly (Goward et al., 1985a). Airborne experimental data sources (design prototypes for the TM, below) have included two Thematic Mapper Simulators (TMS), the Daedalus TMS (flown on the high-altitude ER-2 aircraft, and source of the data used in the present study) with an 8.5-14.0 μm thermal band, and the NS-001 TMS (flown on the C-130B aircraft) with a 10.9-12.3 μm thermal band. These are still in use. Ground resolution is a function of aircraft altitude (typically 28 m from standard ER-2 altitude); data is 8-bit.

The experimental phase ended with the launch of the first Thematic Mapper (TM) on Landsat 4 in 1982; others have followed. The TM thermal band (10.4-12.5 μm) has a ground resolution of 120 m (as opposed to 30 m in the TM shortwave bands); data is 8-bit. Coverage time depends on the particular satellite. A next-generation prototype, the Thermal Infrared Multispectral Scanner (TIMS), is now in use, flown on NASA's ER-2 aircraft. TIMS boasts six bands in the 8-12 μm region; data is 8-bit, and ground resolution is typically 25 m (from standard ER-2 altitude).

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[3]*Resolution* here refers to radiometric resolution, the ability to distinguish subtleties of temperature or brightness (see Glossary).

Remote Sensing of Urban Heat Islands

Initially, remote sensing of urban heat islands was serendipitous. Rao (1972) noticed evident urban signatures on ITOS-1 SR thermal images while studying sea surface temperatures, and suggested thermal remote sensing as an avenue of urban heat island research. However, SR and VHRR radiance resolution was limited, as were the atmospheric correction algorithms available at the time. Nonetheless, it quickly became clear that the urban heat island phenomenon stood out strongly in thermal images, and in fact seemed better defined at least in daytime by surface temperature than by air temperature (see Table 2). Carlson et al. (1977) used VHRR data to produce an isothermal contour map of Los Angeles. Matson et al. (1978) managed to use VHRR data acquired on an exceptionally clear night to compare the mapped heat signatures of Washington, Baltimore, and St. Louis with population maps and to infer recent urban growth; Matson and Legeckis (1980) compared community sizes and their thermal signatures in New England using equivalent VHRR data.

Several early investigators used airborne thermal sensors for heat island studies. Colacino (1978) performed an airborne version of the classic automobile heat island study (cf. Henry et al., 1989) by flying several transects in and around Rome at 700 m height and reading the flightline thermal radiance below the aircraft from a simple radiometer. Pease et al. (1976) and Pease and Nichols (1976) used an airborne multispectral visible/thermal scanner to produce energy budget maps of Baltimore; an important finding was that urban surface temperatures, when analyzed radiometrically, vary strongly at the local scale. Earlier studies had relied on sensors with a lower ground resolution that effectively smoothed surface temperatures over a wider area; ground-based studies of air temperature along automobile-route transects had also fostered the notion of urban heat islands as monolithic entities. Pease et al. (1980) used data from a Skylab 3 orbiting multispectral visible/thermal scanner (ground resolution ~70 m) as input for energy balance modeling. The paper is notable for its cogent discussion of atmospheric problems encountered in thermal remote sensing from space.

NASA launched the first AVHRR and the HCMR in 1978. Since HCMR (and later TM) ground resolution is superior, relatively little urban heat island work has been based on AVHRR imagery, despite the fact that the data from later models is self-calibrating (i.e. contains the necessary information for estimating true ground radiance without ancillary data on the intervening atmosphere at the time the satellite passed over) due to its "split window" thermal bands (see Schmugge, 1989). A second advantage is its ubiquity. As a contributing element to operational weather forecasting, AVHRR data is inexpensive and plentiful. Dousset (1989) took advantage of this fact in a unique study of Los Angeles. By merging many AVHRR scenes of the city, each generated at the same time of a different day, a map of mean temperatures resulted that effectively smoothed out much of the noise caused by day-to-day weather peculiarities. The heat island map thus produced is inherently climatological and yields much more pertinent information on heat sources and sinks than can any single image. Balling and Brazel (1988) performed a similar, more limited analysis of Phoenix, and then compared mean apparent temperature with broad land use categories. Kidder and Wu (1987) analyzed an AVHRR scene of St. Louis under partial snow cover to consider feedback effects involving differential albedo and enhanced melting.

Price (1979) published initial temperature analyses using HCMR data. Thermal inertia, a parameter the HCMM satellite and its sensor were designed to measure, proved illusive in urban situations (Carlson et al., 1981; Galli de Paratesi and Reiniger, 1982). This will be discussed below. Several investigators used HCMR data in conjunction with numerical energy balance models and more complex numerical urban climate models, either to define initial states or for comparison of results. Results of these efforts were, in general, encouraging but inexact. Problems can be traced to (1) weaknesses in modeling the urban canopy (eg. Carlson, 1980; Carlson et al., 1981; Vukovich, 1982; Henry et al., 1989; Lewis and Carlson, 1989); (2) the assumption that urban surfaces viewed from space represent all surfaces in the urban topology (eg. Carlson, 1980; Carlson et al., 1981; Vukovich, 1982; Lewis and Carlson, 1989); and (3) in the early years, inexact algorithms for removing atmospheric effects and sensor artifacts from the data (eg. Carlson, 1980; Carlson et al., 1981; Vukovich, 1982). A full discussion of applicability and limitations is given in Roth et al. (1989; see also Schmugge, 1989). A conclusion often reached during this phase (see especially Goward et al., 1985a) was that rural-urban albedo differences as estimated from space imagery, at least in the heavily vegetated eastern U.S., seemed to factor less in the formation of urban heat islands than did differences in vegetation cover and the consequently diminished urban loss of heat to evapotranspirative cooling. Such a conclusion may not be warranted, of course, in regions with arid summer conditions, such as California, since the rural summertime landscape contains little freely transpiring vegetation aside from irrigated crops.

Cost may be a factor, but relatively few urban heat island studies have used TM data. Carnahan and Larson (1990), while using TM data for unrelated research, discovered a TM thermal image in which Indianapolis shows up as a cold region, which they termed an “urban heat sink”. They attributed part of the effect to the city’s background at the time (10:00 AM May 10, 1987) — dry, tilled, unvegetated agricultural soils, the surface layer of which would heat quickly in the morning due to its low effective thermal mass (conduction would be poor since recent tilling had left the dry soil in a disaggregated state). In contrast, urban fabrics tend to include surfaces of high thermal mass, both heating and cooling slowly, so a cool urban core at that time of day in summer is to be expected. Another part of the effect observed by Carnahan and Larson is probably due to viewing angle and urban geometry: much of the city's absorbed heat at that hour was probably stored in vertical walls facing ESE.

Shortwave (visible and near-infrared) remote sensing is also a necessary component of urban heat island research, not only as an aid in analyzing thermal image data, but for quantifying albedo and vegetation for purposes of estimating surface energy budgets. Important sensors include the Multi-Spectral Scanner (MSS, with four shortwave bands) orbited on all Landsat satellites to date, the TM (six shortwave bands), seven (NS-001) or ten (Daedalus) shortwave TMS bands, and the next-generation prototype Airborne Visible-InfraRed Imaging Spectrometer (AVIRIS), with 220 10-bit shortwave bands, currently flown experimentally on the ER-2. There is increasing use of the French Système Pour l'Observation de Terre (SPOT), with four shortwave bands (one of them a panchromatic visible band of high spatial resolution). The USSR also sold satellite data recently, but we have yet to see published use of it. All studies that couple remote sensing and numerical modeling must rely on shortwave image data (for net shortwave flux estimates, and to generate the vegetation indices that allow latent heat flux estimates), while many other studies have also used shortwave images for ancillary purposes. Brest (1987, 1989a, b) conducted urban/rural albedo comparisons of the Hartford, CT area during different seasons, using MSS data. He found marked seasonal changes; however, seasonality will affect shortwave fluxes, and hence rural-urban albedo contrasts, differently in different biomes. He also looked for and found no anthropogenic surfaces mimicking the visible/NIR ratios of green vegetation. Forster (1985) also experimented with analyzing vegetation against difficult urban backgrounds.

At present, the research community can acquire data of higher spatial resolution, spectral resolution, and numerical precision than has previously been possible. The data also offers unprecedented thermal or reflectance accuracy thanks to advances in sensor design and calibration, and to advances in atmospheric correction algorithms (Chavez, 1988, 1989; Kniezys et al., 1980, 1983, 1988; Richter 1989, 1990. For further discussion see Tanré et al., 1981, 1987; Chen and Ohring, 1984; Kaufman, 1985; Slater et al., 1986; Brest and Goward, 1987; Crippen, 1987; Isaacs et al., 1987; Slater 1987; Holm et al., 1989; Koepke, 1989). More difficult to compensate for is the special problem of urban atmospheres, a problem crucial to calculating urban energy budgets from remotely sensed data but of relatively little import to general remote sensing problems.

Particulate concentrations can be very high in urban atmospheres, which affects rates of Mie scattering[4], but anthropogenic trace gases present a more formidable atmospheric correction problem (Bergstrom and Viskanta, 1973; Herman and Browning, 1975; Liou and Sasamori, 1975; Pease et al., 1980; Whitehead, 1989; Hänel et al., 1990; White, 1990). Other work falls into two categories: analyses of concentrations and circulations (Lea, 1968; Wakimoto and McElroy, 1986) and analyses of effects on energy budgets (Mateer, 1961; Atwater, 1971 a, b; Uthe and Russel, 1974; Ackerman et al., 1976; Ackerman, 1977; Peterson and Stoffel, 1980). White (1990) offers a useful review and analysis; Hänel et al. (1990) offer new evidence of the magnitude of effects.

The atmospheric correction problem can most easily be understood by imagining you are viewing an automobile through mist with bright sun behind you. The automobile is well illumined by sun (and by bright mist), but you see it dimly. This is partly because some light is lost in the mist on its way from the car to you, but largely it is because the mist between you and the car, although not opaque, is itself shining in the sunlight. The task in correcting a remotely sensed image is to mathematically remove the mist. Instrument sensitivity can compensate for the light lost, but the brightness of the mist must be accurately subtracted. This accomplished, the automobile will still appear hazy: bright reflections on the chrome will each have a halo, and in fact *all* the light reflected will have been scattered in the same halo pattern on its way to you. This patterned haze, too, must be accurately reassigned back to the originating pixel. (Technically, our car-in-the-mist model only describes Mie, or particulate, scattering; however, because the atmosphere increases exponentially in density towards the earth's surface the Rayleigh, or molecular, scattering also contributes a Mie-like pattern of scattering to light from objects viewed from space or from high altitudes.) In thermal wavelengths the atmosphere itself glows due to its temperature, so the analogy breaks down.

Limitations of the corrected data are now better understood than previously. In early studies urban climatologists sometimes ran afoul of the remote sensing community's inaccurate use of the word "albedo" for apparent brightness. Remotely sensing true albedo requires a Lambertian (smooth, and "flat" as opposed to shiny) reflection surface, whereas urban images contain a motley collection of surfaces and shadows. Similarly, remotely sensed surface temperature and thermal inertia estimates are inherently biased by the topological subset viewed: rooftops, treetops, and open ground. Vegetation

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[4]Mie scattering is what makes things look hazy and limits visibility; it's caused by particles and droplets suspended in the air.

presents special problems in the urban environment, both in terms of estimating vegetation itself against the nonuniform urban background, and secondarily deducing evapotranspiration.

It is important to understand the distinction, however, between the accuracy of the data itself, which is now potentially excellent, and its limitations. For example, no instrument looking vertically down on a city can yield information on the temperature or the albedo of vertical walls: thus a sometimes large percentage of the urban surface "disappears" when the urban region is analyzed from directly above. Similarly, if a scene contains shadows, it is up to the investigator to distinguish between the darkness contributed by shade and that due to dark surfaces: many pixels in the image will appear artificially dark because shadows have been cast onto otherwise lighter materials. Shiny (specularly reflective) surfaces present an analogous problem; if they reflect the sun directly into the sensor, apparent albedos can reach several hundred percent, while if they reflect light away then the surfaces will seem to be absorbing light that they are not. All such errors result from the simplifying assumption that the urban surface is Lambertian and reflects light equally in all directions.

General Urban Remote Sensing

Parameters other than energy budget estimates are also pertinent to urban heat island research. A very brief review of other aspects of urban remote sensing is included here. Aerial photography, of course, is the mainstay of innumerable urban analyses, from traffic studies to tax assessments. Another very large body of literature concerns the rather intractable problem of automated land cover classification of urban digital imagery using techniques developed for classification of more homogeneous land covers in natural settings (see, for example, Toll, 1984; Khorram et al., 1987; Baraldi and Parmiggianni, 1990; Leak and Venugopal, 1990). Novel approaches include those of Forster (1983) and Wharton (1987). Automated land cover classification at the urban/rural interface also presents a challenge: see Jensen (1979), Jensen and Toll (1982) and Martin and Howarth (1988); or see Gong and Howarth (1990) for a different approach. For an example of a multitemporal study to analyze urban change see Martin (1989). Haack (1983) includes a general discussion of remote sensing in the urban context and the resolution paradoxes that can result.

Studies of urban heat island phenomena and their mitigation require accurate characterizations of pertinent aspects of the urban landscape. A great deal of analysis of remotely sensed data is aimed at classification rather than characterization (see Johnson and Howarth, 1987). The distinction is important (contrast, for example, the classification approaches of Satterwhite and Henley, 1987; Townshend, 1987 with the characterization approach of Smith et al. 1990a, b). If a neighborhood is classified as "Urban Terrain Zone A-5" (cf. Ellefsen, 1989; also eg. Alexander, 1976; Anderson et al., 1976) then all spatial units within that area acquire *typical* values, for Urban Terrain Zone A-5, of pertinent aspects such as roof area index, ratio of building height to inter-building distance, and thermal inertia. On the other hand, if an image is characterized for "greenness" using the Normalized Difference Vegetation Index (NDVI), then each pixel is tagged with an individual scalar value locally derived. A time may come when urban classification schemes pertinent to the requirements of heat island analysis exist, and of course practical considerations may currently dictate generalization to classification values. In general, however, classification should be the *final* step in terrain analysis of any kind: preliminary analytical steps should produce a series of scalar attributes (characterizations) designed to convey maximal information, as accurately as possible, to the final classification phase. In the near term, this will mean reliance on manual methods using data such as aerial photography (vertical and oblique, cf. Ellefsen, 1989), zoning and similar maps, and through field work.

Future Directions

Machine analysis of digital data is currently in the midst of a revolution, and new methodologies will very likely transform the spectrum of available characterization approaches in the near future. In addition to the spectral-mixture approach of Smith et al. (1990 a, b, above; see also Adams et al., 1986), techniques borrowed from artificial-intelligence research are coming into use. Argialas and Harlow (1990) provide a thorough discussion and overview (see also Wharton, 1987; Benediktsson et al., 1990; Lam, 1990; Møller-Jensen, 1990; Srinavasan, 1990).

The present study focuses on analyzing the potential of remote sensing approaches to allow straightforward comparison of different urban landscapes, both between cities and within a given city. The urban fabric is defined by architectural styles, by the spacing and height of structures, by the design of streets, and by the use of open space. These individual elements combine to define a landscape of varying patterns of energy transfer, with greater and lesser absorption, greater and lesser storage, and greater and lesser transfer to latent heat through evapotranspiration. It should be possible to provide image-based maps that effectively illustrate the relative energetics of different parts within a city, so that planning agencies can provide for effective and intelligent management in the future.

However, current methods are limited by the unknown magnitude of the effects of simplifying assumptions. As discussed above, the exclusion of vertical surfaces from remotely sensed data precludes accurate assessment of the albedo and thermal landscapes. Research is needed using forward oblique scanners at moderate altitudes to allow full analysis of global radiation budgets in urban environments at a variety of sun angles. Research is also needed in analyzing vegetation in the urban landscape to determine the effects of differing backgrounds and differing moisture stresses both above and below ground due to limited percolation, canyon environments, heavy particulate loads, and other factors: estimation of canopy health and transpiration rates may be more complex than assumed.

Urban surface energy models have also been limited by their simplifying assumptions. As computers and models alike become more powerful, it will be possible to model the complex energy storage and release patterns of hollow, partially open buildings, and of realistic vegetation canopies, and to model radiant energy exchanges in realistically complex sub-canopy strata, especially within urban canyons. With reliable three-dimensional mesoscale models, research can focus on ways the urban fabric affects mesoscale circulation. Eventually it will be possible to engineer that circulation through the spacing and pattern of changes in the urban fabric.

Table 1. Sensors frequently encountered in urban heat island studies

Sensor Acronym	Sensor Name	Year Started	N of Bands: Shortwave / Thermal	Ground Resolutionat nadir
SR	Scanning Radiometer	1970	1 / 1	7.4 km
VHRR	Very High Resolution Radiometer	1972	1 / 1	1 km
		1978	3 / 1	1 km
AVHRR	Advanced Very High Resolution Radiometer	1978, 79	3 / 1	1.1 km
		1981	3 / 2	1.1 km
MSS	LandSat Multi-Spectral Scanner	1972	4 / inop.	80 m
HCMR [HCMM]	Heat Capacity Mapping Radiometer [Heat Capacity Mapping Mission]	1978	1 / 1	600 m
TMS	Daedalus Thematic Mapper Simulator	1980	10 / 1	25 m
TMS	NS-001 Thematic Mapper Simulator	1985	7 / 1	varies by alt.
TM	LandSat Thematic Mapper	1982	6 / 1	30 m / 120 m
SPOT	Système Pour l'Observation de Terre	1986	3 & 1 / 0	30 m & 10 m
TIMS	Thermal Infrared Multispectral Scanner	1985	0 / 6	25 m
AVIRIS	Advanced Visible-InfraRed Imaging Spectrometer	1989	220 / 0	20 m

Table 2. Remote sensing studies of urban heat islands summarized

Study	City	Date of Study	Approximate Time of Day	~ΔT, °C (Radiant)	Sensor	Thermal Band (μm)	Imaging Sensor?	Platform	Other aspects of study
Rao 1972	{New York NY, Philadelphia PA, Baltimore MD, Washington DC}	10/1970	0300	+3.5	SR	10.2-12.5	Yes	ITOS-1	
Pease et al. 1976, Pease and Nichols 1976	Baltimore MD	05/1972	0530	+6.0	ERIM M-7 MSS	9.8-11.7	Yes	Aircraft	Derived energy budget parameters and performed modeling
			1030	+7.0					
			1400	+20.0					
Carlson et al. 1977	Los Angeles CA	03/1975	0900	+11.0	VHRR	10.5-12.5	Yes	NOAA-3	
			2000	+5.0					
Colacino 1978	Rome, Italy	06/1975	0600	+6.0	Barnes PRT-5 radiometer	8.0-13.0	No	Aircraft	Compared above-canopy air temperature
		01/1976	1400	+24.0					
			0600	+1.0					
			1400	+3.5					
Matson et al. 1978	Louisville KY	07/1977	2100	+6.5	VHRR	10.5-12.5	Yes	NOAA-5	
	Baltimore MD			+5.2					
	Washington DC			+5.2					
	Cincinnati OH			+5.1					
	Indianapolis IN			+4.5					
	Dayton OH			+4.5					
	St. Louis MO			+4.4					
	Richmond VA			+3.8					
	Columbus OH			+3.3					
	Kansas City MO			+3.2					
	Petersburg VA			+2.6					
Price 1979	{Hudson R. Vy. region, NE U.S.}	06/1978	1330	+17.0 to +6.8	HCMR	10.5-12.5	Yes	HCMM	Compared air temperatures, populations
Carlson 1980	Washington DC	06/1978	0230	+3.5	HCMR	10.5-12.5	Yes	HCMM	Performed extensive modeling
			1330	+7.0					
Matson and Legeckis 1980	{Boston MA, Providence RI, etc.}	05/1978	0900	+8.0	VHRR	10.5-12.5	Yes	NOAA-5	
Pease et al. 1980	{Washington DC, Baltimore MD}	08/1973	0900	+12.0	S-192 scanner	10.5-12.5	Yes	Aircraft	Derived energy budget parameters and performed modeling
Carlson et al. 1981	Los Angeles CA	05/1978	0230	+2.0	HCMR	10.5-12.5	Yes	HCMM	Includes derivative modeling
	St. Louis MO	06/1978	1330	+6.0					
			0230	+2.0					
			1330	+7.5					

Table 2, continued

Study	City	Date of Study	Approximate Time of Day	~ΔT, °C (Radiant)	Sensor	Thermal Band (μm)	Imaging Sensor?	Platform	Other aspects of study
Vukovich 1982	St. Louis MO	06/1978	0230	+2.3	HCMR	10.5-12.5	Yes	HCMM	Includes derivative modeling
		02/1979	0230	+2.7					
		09/1979	1330	+6.5					
			1330	+3.8					
			1330	+2.4					
			1330	+4.4					
Goward et al. 1985a	Hartford CT	06/1978	1330	--	HCMR	10.5-12.5	Yes	HCMM	Performed vegetation and other analyses
Dousset 1989	Los Angeles	08/1984 and 08/1985 combined	various combined	--	AVHRR	various 10.3--12.5	Yes	NOAA -6,-7,-9,-10	Created image of mean conditions by co-registering and averaging 84 images
Kidder and Wu 1987	St. Louis MO	(Snow)	(Night)	+3.0	AVHRR	10.3-11.3	Yes	NOAA-7	Focuses on energy budget dynamics under snow cover
			(Day)	+2.5					
Balling and Brazel 1988	Phoenix AZ	06/1986 through 08/1986 combined	1400	-3.0	AVRR	10.3-11.3	Yes	NOAA-9	Created map of mean conditions; attempted correlation with land use categories
Henry et al. 1989	Gainesville FL	05/1978	0230	+5.0	HCMR	10.5-12.5	Yes	HCMM	Compared with results of modeling and of automobile air temperature transect
		11/1978	1330	-6.0					
		12/1978	0230	+9.0					
		03/1979	1330	+5.0					
		02/1979	1330	+6.0					
			0230	+2.0					
Lewis and Carlson 1989	Montreal, Quebec	06/1985	0230	+4.0	HCMR	10.5-12.5	Yes	HCMM	Some modeling; compared with studies of St. Louis and Los Angeles
			1330	+7.0					
Roth 1989	Vancouver BC	11/1983	1400	+1.0	AVHRR	10.5-11.5	Yes	NOAA-7	Compared with air temperature data; discussion of methodological problems, urban meteorology
	‘	01/1984	1400	+1.6				NOAA-7	
	‘	01/1985	1400	+2.7				NOAA-9	
	‘	06/1985	0300	+3.5				NOAA-9	
	‘	07/1985	0400	+3.5				NOAA-9	
	‘	08/1985	1400	+7.5				NOAA-9	
	‘	09/1985	1900	+4.5				NOAA-8	
	‘	10/1985	1400	+4.0				NOAA-9	
	Seattle WA	02/1986	1400	+5.0				NOAA-9	
	Los Angeles CA		1400	+5.5				NOAA-9	
	Vancouver BC		0330	+2.7				NOAA-9	
Carnahan and Larson 1990	Indianapolis IN	05/1987	1000	-6.4	TM	10.5-12.5	Yes	LANDSAT-5	Discussed "heat sink" phenomenon

GLOSSARY OF TERMS

Albedo: Loosely, "whiteness". How much of the energy in the complete solar spectrum that a surface or an object reflects. Snow and sand have high albedos, tar and soot low. Used loosely in the remote sensing community to mean apparent albedo when viewed from overhead; this can be misleading.

AVHRR: Advanced Very High Resolution Radiometer, successor to VHRR, currently used on polar-orbiting weather satellites.

AVIRIS: Advanced Visible Infrared Imaging Spectrometer, experimental state-of-the-art sensor flown on NASA's ER-2 aircraft. Produces seventeen megabytes of data per second.

Biome: Regional-scale biotic community, eg. savanna, tundra, boreal forest.

Daedalus: As used in this paper, one of NASA's two TMS sensors.

Digital Image: An image recorded as a series of numbers corresponding to pixels (q.v.), as opposed to an analog image recorded as a series of magnetic moments (video) or silver halide oxidation states (traditional photographs). This corresponds to the difference between digital music on a compact disk, versus analog music on a vinyl record.

ER-2: "Earth Resources 2", the civilian version of the U-2 spy plane as flown by NASA. Unmodified planes are still referred to by NASA as U-2.

Evapotranspiration: The flux of water evaporating freely from surfaces, combined with the flux of water transpired via the leaves and stems of plants.

HCMM: Heat Capacity Mapping Mission, the name of the program and satellite on which the HCMR was orbited.

HCMR: Heat Capacity Mapping Radiometer, experimental sensor used on the HCMM for comparing explicitly daytime and nighttime surface temperatures.

Heat Island: See *urban heat island*.

ITOS: Improved TIROS Operational Satellite, weather satellite.

LST: Local Solar Time, the time of day as a sundial would give it. This is important for comparing data in terms of the daily cycle of solar warming and nighttime cooling.

Mie Scattering: Scattering of light due to particulates and droplets suspended in the atmosphere. The cause of haze effects, abnormal reddening at sunset, etc.

NASA: National Aeronautics and Space Administration.

NOAA: National Oceanic and Atmospheric Administration.

NS-001: One of NASA's two TMS sensors.

Pixel: "Picture Element". Digital images are composed of rows and columns of closely spaced spots, each assigned a brightness (or color) according to the brightness level (or levels) the sensor recorded when it produced the image. Each spot is a pixel. The nominal size, on the ground, of each pixel in an image is often given as a measure of spatial resolution, and often this is accurate if the pixels are the limiting resolution factor in forming an image. However, they are not strictly equivalent: the Hubble space telescope, for example, currently cannot resolve as much information as its pixels can record.

Rayleigh Scattering: Scattering of light due to molecules in the atmosphere; makes the sky blue.

Remote Sensing: Loosely, any means of gathering information about a location without sending a person or instrument to the location itself. Thus, remote sensing includes ærial photography, satellite imagery, sonar, radar and the like.

Resolution, Radiometric: The ability of a sensor to distinguish between levels of brightness. The human eye can distinguish between about thirty shades of gray at a time (if we refocus on brighter lights or darker shades, our eyes adjust). Photographic films yield a gray scale of about 20 shades, with some variation; photographic prints yield a gray scale near 10. Electronic sensors vary. MSS data is capable of 64 shades, TM of 256, and AVIRIS of 1024. Often, however, sensor upper and lower bounds are set beyond the range of brightness encountered in an image.

Resolution, Spatial: The ability, in an image, to distinguish fine detail. In a sensor this is given in terms of solid angle, since a given camera, for instance, can yield a more detailed picture from closer up than from farther away. Since many satellites orbit at a fixed distance from earth, the same information can be given in terms of distance on the ground, usually the nominal dimension of a single image pixel, eg. 1100 m for AVHRR, 79 m for MSS, 30 m for TM shortwave bands (see *pixel*).

Resolution, Spectral: The ability of a sensor to distinguish between adjacent wavelengths on the electromagnetic spectrum. For example, black-and-white film yields a single image from wavelengths between about 0.3 and 0.7 μm. A color slide, on the other hand, divides the same wavelengths into three images (one is dyed yellow, one magenta and one cyan): the slide has higher spectral resolution, and thus can carry more information. The state of the art AVIRIS sensor, on the other hand, divides the wavelengths between 0.41 and 2.45 μm into as many as 220 images. The human eye can only make sense of three images at a time due to the nature of our color vision. Pigeons can make sense of five at a time.

SPOT: Système Pour l'Observation de Terre, the French earth-observing satellite. It has a single broad shortwave band that has 10 m ground resolution, and three narrow bands in the same part of the spectrum with poorer resolution.

SR: Scanning Radiometer, early precursor to VHRR.

Synoptic: A single view of simultaneous conditions. The Weather Service, for example, goes to some lengths to interpret data gathered by a myriad of observers in order to produce a synoptic map, i.e. a map of widespread conditions at a particular instant in time.

Thermal: As used in this paper, thermal denotes radiation, sensors and images relating to the part of the electromagnetic spectrum (the thermal infrared is typically given as 8-20 μm) in which the earth (and objects on it) shine far more brightly by their own heat than by reflected solar radiation. Thus relative brightness can be analyzed to determine surface temperatures.

Thermal Inertia: The relative speed with which a substance or surface heats or cools. Often used in heat island studies in the practical sense of how rapidly the ground surface or a structure on it heats up in the sun or returns to air temperature at night, rather than the absolute sense of molecular response to absorbed energy (specific heat).

TIMS: Thermal Infrared Multispectral Scanner, prototype state-of-the-art thermal sensor flown on NASA's ER-2 aircraft.

TIROS: Television Infrared Observing Satellite, weather satellite.

TM: Thematic Mapper, the second-generation multispectral scanner flown on the Landsat platforms. Note that the original line of MSS scanners continued to be flown on the same platforms.

TMS: Thematic Mapper Simulator, one of two different instruments flown by NASA on aircraft. Despite their contrasting characteristics, both can yield data that mimics TM data.

Urban Fabric: A term used to denote the complex pattern of buildings and other structures, streets and other transportation lanes, lawns, trees, water bodies, parking lots, and all the many components that make up the overall physical entity that is a city.

Urban Heat Island: The observed tendency for air temperatures within urban regions to be several degrees higher than in the surrounding rural region. Causes vary by time of day, season, and location but are primarily low effective albedo, reduced vegetation cover, and anthropogenic waste heat.

VHRR: Very High Resolution Radiometer, analog sensor on early weather satellites that replaced the SR.

Annotated Bibliographies

Note: The three annotated lists below are divided by subject area. Inevitably, some papers discuss matters that belong in more than one list. Such references are listed in their primary subject area, but are marked with asterisks, the number of which denotes their secondary subject area.

I. Remote Sensing and the Urban Context

Balling, Robert C; Brazel, Sandra W. High-resolution surface temperature patterns in a complex urban terrain. *Photogrammetric engineering and remote sensing;* 1988; **54**(9): 1289-1293.

High-resolution here means AVHRR; the terrain is Phoenix. Temperature maps are constructed manually from averaged sensor data. There is some attempt to correlate temperature elevations with land use.

***Brest, Christopher L. Seasonal albedo of an urban/rural landscape from satellite observations. *Journal of climate and applied meteorology;* 1987; **26:** 1169-1187.

Hartford, CT; similar to heat island conference paper, below.

Brest, Christopher L. Seasonal albedo of an urban/rural landscape from satellite observations (addenda); February, 1989. 35 p.

A superset of the graphics and tables included in his heat island conference paper (below); in Heat Island Project archives at LBL.

***Brest, Christopher L (Centel Federal Services, NASA Goddard Institute for Space Studies, New York, NY 10025). Seasonal albedo of an urban/rural landscape from satellite observations. Garbesi, Karina; Akbari, Hashem; Martien, Phil, eds. *Controlling summer heat islands. Proceedings of the workshop on saving energy and reducing atmospheric pollution by controlling summer heat islands;* Feb 23-24, 1989; Berkeley, CA: Energy Analysis Program, Applied Science Division, Lawrence Berkeley Laboratory; November, 1989: 238-255. 351 p.

Discusses calibration of satellite measurements for determinations of true albedos on the ground. Studies use of MSS data for classification purposes, across land cover types and through an annual cycle, for the Hartford, CT area. Uses 27 MSS scenes; divides land cover into 13 categories. Salient points are (1) seasonality can have a marked influence on albedo and other characteristics of reference to land cover classification, (2) under current practices, few anthropogenic surfaces display the high near-infrared albedo of vegetation.

Difficulties are (1) this is MSS data, not TM data, so the concepts are good but the regression coefficients irrelevant; (2) seasonality in Hartford is obviously different from that in CA, so the seasonal patterns are instructive but in no wise definitive; (3) binary classification of pixels or groups into "vegetation" or "non-vegetation" based on their near-IR/visible ratios before further processing seems certain to produce difficulties in precisely the partially-vegetated areas of critical interest to heat-island mitigation.

Carlson, Toby N. Applications of HCMM satellite data to the study of urban heating patterns. Remote estimate of the surface energy flux, moisture availability and thermal inertia over urban and rural terrain. University Park, PA: Dept. of Meteorology, Pennsylvania State University; December 1980; HCM-001. 62 pp. Available from: Clearinghouse for Federal Scientific and Technical Information, Springfield VA 22151.

Note: Prepared for NASA Goddard Space Flight Center.

This is an overview paper summarizing several years' research, much of which is pertinent. Contributions include a mesoscale model of energy flux designed for urban settings, and early use of good-resolution satellite thermal data. The Heat Capacity Mapping Radiometer included a visible and a thermal band; ground resolution was 600 m; the thermal band nominally included 10.50 - 12.50 micrometers; data acquisition was 1:30 pm and 2:30 am LST accurate to 0.4 K. (TM thermal band ground resolution is 120 m; it nominally includes 10.40 - 12.50 micrometers; data acquisition originally was 9:45 am LST.) Conclusions include findings that thermal inertia and moisture availability are dominant forces in mesoscale urban heat island meteorology; that (primarily in the East) diminished vegetation and limited latent heat flux are the main elements in summer urban heating; that radiant heat flux rather than sensible is important in human discomfort.

Vukovich (1982) states this work failed to account for a 5.5°C HCMR calibration error, and thus all results are of questionable validity.

Carlson, Toby N; Augustine, J N; Boland, Frederick E. Potential application of satellite temperature measurements in the analysis of land use over urban areas. *Bulletin [American Meteorological Society];* 1977; **58:** 1301-1303.

Early NOAA-3 VHRR data for day and evening Los Angeles 3/29/75, mapped out with isotherms.

Carlson, Toby N; Dodd, Joseph K; Benjamin, Stanley G; Cooper, James N. Satellite estimation of the surface energy balance, moisture availability and thermal inertia. *Journal of applied meteorology;* 1981; **20(1): 67-87.

Studies L.A. basin and St. Louis using HCMM thermal radiances; analyzes with one-dimensional model. Finds that moisture availability decreases toward city centers; can find no coherent pattern of apparent thermal inertia. Concludes that heat island effect is due to greater daytime storage from elevated temps due to low moisture availability.

Carnahan, Walter H; Larson, Robert C. An analysis of an urban heat sink. *Remote sensing of environment;* 1990; **33:** 65-71.

Landsat image of Indianapolis at 10 AM May 10 1987 shows surrounding cultivated but non-vegetated fields with soil in unusually dry state to be warmer than downtown. Presumably much of the early insolation is stored in vertical walls downtown, invisible to TM? Also there may be cloud complications -- a cloud over part of the city is ill-defined with semi-transparent portions: this could extend farther in a sub-clinical manner. City should be expected to be cooler than bare earth at that time of day due to greater thermal inertia in any event.

Colacino, M. Infrared radiometric measurements for the study of Rome urban heat island. *Archiv fur meteorologie, geophysik und bioklimatologie. Serie B;* 1978; **26:** 207-217.

Study relied on a non-imaging radiometer mounted on a plane flying at 200 m. Resolution of flight patterns and of ground station network prevents meaningful comparison of maps of ground-level air T, air T at 200 m, and surface T.

***Dousset, Bénédicte. AVHRR-derived cloudiness and surface temperature patterns over the Los Angeles area and their relationships to land use. *Proceedings of International Geosciences and Remote Sensing Symposium (IGARSS);* 1989; 2132-2137.

Demonstration of excellent methodology involving co-registering images for many dates and summing them into a single image; this has the distinct advantage of eliminating nonce-effects from observed patterns. Particular temporal, meteorological etc. conditions are selected for.

Fezer, F. Climatic change after regeneration in the oldest quarter of Heidelberg. *Landscape and urban planning;* 1990; **19:** 47-54.

Regeneration consisted in removing accumulated outbuildings from courtyards (the interiors of blocks), with some tree planting. Aspect ratio and air circulation increased, and temperature conditions gravitated toward rooftop level conditions somewhat.

Forster, Bruce C. Some urban measurements from Landsat data. *Photogrammetric engineering and remote sensing;* 1983; **49(12): 1693-1707.

Includes a useful general review of remote sensing in urban analysis, from very early work; extensive references. Notes the special problem of background contributions to pixels in an area of marked patterning such as an urban landscape. Notes photo analysis tended to be for population and living conditions, whereas space imagery analysis has tended to be for land use classification. Notes urban land cover classes tend to be continua rather than discrete (eg. cotton vs. barley). Present study compared MSS and 1:15000 photography; assumes Lambertian reflectance; includes chart of apparent albedos of eg. some roofing, paving and vegetation covers by MSS band. Does not include accurate atmospheric corrections.

Galli de Paratesi, Sergio; Reiniger, Peter, eds. Heat Capacity Mapping Mission, investigation no. 25 (Tellus Project), final report to National Aeronautics and Space Administration Goddard Space Flight Center: Commission of the European Communities Joint Research Centre, Ispra Establishment; 1982; HCM-025. 239 pp.

Contains useful information on instrument calibration, together with a number of reports on heating patterns in urban/rural and other landscapes. The thrust of the project was to demonstrate feasibility; thus positive results typically encompass little more than demonstration of the interpretability of data. However, some of the speculation included is stimulating and valuable.

Pages 117-119 concern thermal inertia mapping and classification, including urban. Part 3 (pp 163-176) concerns anthropogenic heat release.

Goward, Samuel N; Cruickshanks, George D; Hope, Allen S. Observed relation between thermal emission and reflected spectral radiance of a complex vegetated landscape. *Remote Sensing of Environment;* 1985; **18:** 137-146.

Compares HCMR thermal data, MSS "greenness index" data, and two measures of albedo over an urban/rural landscape including Hartford, CT, with soil moisture at capacity. Concludes vegetation dominates albedo as a determinant of longwave flux. An important finding is that the HCMR visible sensor is so biased toward the near-infrared that it functions almost as a "greenness" indicator on its own, and does not provide adequate albedo information.

Henry, James A; Dicks, Steven E; Wetterqvist, Orjan F; Roguski, Stephen J. Comparison of satellite, ground-based, and modeling techniques for analyzing the urban heat island. *Photogrammetric engineering and remote sensing;* 1989; **55**(1): 69-76.

Compares HCMM data (several sets) with interpolated map from drive-around, and results from a thermal-resultant model based on land-use categories (not an energy-balance model). Rough agreements resulted.

***Jensen, John R; Toll, David L. Detecting residential land-use development at the urban fringe. *Photogrammetric engineering and remote sensing;* 1982; **48**(4): 629-643.

MSS band 5 data were used in multitemporal analysis with complex change-detection algorithms. Classification applies to urban vs rural only. Accuracy remains moderately poor.

Kidder, Stanley Q; Wu, Huey-Tzu. A multispectral study of the St Louis area under snow-covered conditions using NOAA-7 AVHRR data. *Remote sensing of environment;* 1987; **22:** 159-172.

The curious thing about this study is the fact that the snow boundary pretty closely coincides with the position of St. Louis. Reports large differences in albedo etc; however, it's not clear at all whether this should be attributed to enhanced melting of what was surely very marginal snow cover, or to effects of shadows, street clearing, etc. The heat island appears "normal" under snow conditions.

Lewis, John E Jr; Carlson, Toby N. Spatial variations in regional surface energy exchange patterns for Montreal, Quebec. The Canadian Geographer; 1989; 33(3): 194-203.

Using HCMR data, maps and models Montreal surround; note is on island in St. Lawrence,

includes tall hill in park. Results not completely intuitive. Problems may stem from use of R/NIR band for apparent albedo; substrate characterization re. thermal inertia. Pattern does look similar to previous studies in St. Louis, Los Angeles. Not sure conclusions are entirely warranted.

Matson, Michael; Legeckis, Richard V. Urban heat islands detected by satellite. *Bulletin [American Meteorological Society];* 1980; **61**(3): 212.

A very brief note to go with the issue's cover image, a VHRR image density-sliced to correspond to approximate surface temperatures. A number of "hot spots" (not all of them urban) are visible in the clear-atmosphere image of New England.

Matson, Michael; McClain, E Paul; McGinnis, David F Jr; Pritchard, John A. Satellite detection of urban heat islands. *Monthly weather review;* 1978; **106**(12): 1725-1734.

Unusually clear atmospheric conditions 7/28/77 allowed a nighttime NOAA-5 VHRR image enough radiance resolution to serendipitously show heat island effects across much of the eastern and midwestern U.S. The Baltimore-Washington and St. Louis areas were enlarged and examined in detail, comparing the radiance map with Census maps of population density. Resolution ~ 1 km, band 10.5-12.5 micrometers, analog broadcast.

Oke, T R. The micrometeorology of the urban forest. Philosophical Transactions of the Royal Society of London. Series B. Biological Sciences; 1989; **324:** 335-349.

A fairly extensive discussion, with particular reference to effects on human comfort, energy use, and air quality. Notes that there is a void in the literature of studies of mesoscale urban tree densities and effects.

**Pease, Robert W; Jenner, Carol B; Lewis, John E Jr. The influences of land use and land cover on climate: an analysis of the Washington-Baltimore area that couples remote sensing with numerical simulation. Washington, DC: U.S. Department of the Interior; 1980. 39 p. (Geological Survey professional paper; (1099-A)).

Proposal refers to this paper re. remote sensing, land use/ land cover changes. Study was of an early (Skylab 3) trial of space-platform thermal and multichannel visible scanner data (resolution ~70m) use for surface energy budget analysis mapping. Independent land use classification -based numerical modeling produced comparison results. The real strength of this paper is its extremely thorough discussion of the problems inherent in using space-based data, especially discussions of aerosol scattering and trace-gas absorption in the thermal band.

Pease, Robert W; Lewis, John E Jr; Outcalt, Samuel I. Urban terrain climatology and remote sensing. *Annals of the Association of American Geographers;* December 1976; **66**(4): 557-569.

Compares pattern of surface temperatures obtained using an aircraft-mounted thermal scanner with surface temperature predictions obtained using a mesoscale boundary-layer model (which in turn relies on albedos mapped by the same aircraft-mounted sensor). Study area is Baltimore, with three replicated flights in one day, the flight path covering a variety of urban landscape types. Results show qualitative agreement; this paper effectively proves that urban heat islands are patchwork rather than monolithic.

Pease, Robert W; Nichols, David A. Energy balance maps from remotely sensed imagery. *Photogrammetric engineering and remote sensing;* 1976; **42**(11): 1367-1374.

An early experiment in creating synoptic maps of real energy budget parameters, using an aircraft-mounted thermal and optical scanner (ERIM-7). Maps are based on apparent albedo, apparent surface temperatures. Baltimore.

Price, John C. Assessment of the urban heat island effect through the use of satellite data. *Monthly weather review;* 1979; **107**(11): 1554-1557.

Early use of HCMM data for observing heat island effect (NE U.S.), with some temperature parameters calculated although data was initially analog.

Rao, P Krishna. Remote sensing of urban heat islands from an environmental satellite. *Bulletin [American Meteorological Society];* 1972; **53**(7): 647-648.

This represents the first published account of satellite (Improved Tiros Operational Sat ITOS-1) sensing of urban heat island effects. [Resolution was 7.4 km.] It simply notes the general pattern observed along the urban corridor of eastern North America 10/19/70, and discusses the possibilities of using satellite data as an urban heat island research tool.

Roth, M; Oke, T R; Emery, W J. Satellite-derived urban heat islands from three coastal cities and the utilization of such data in urban climatology. *International journal of remote sensing;* 1989; **10**(11): 1699-1720.

This is mainly a discussion of use of low-resolution (600 m and greater) thermal data, and the study reported is based on such data. However, there follows the most lucid discussion of the utility and limitations of scanned thermal data yet encountered, together with an extremely cogent discussion of the general problem of urban temperature analysis and urban meteorologic modeling in general.

**Schmugge, Thomas J (USDA Hydrology Laboratory). Satellite observations of surface temperature. Garbesi, Karina; Akbari, Hashem; Martien, Phil, eds. *Controlling summer heat islands. Proceedings of the workshop on saving energy and reducing atmospheric pollution by controlling summer heat islands;* Feb 23-24, 1989; Berkeley, CA: Energy Analysis Program, Applied Science Division, Lawrence Berkeley Laboratory; November 1989: 191-195. 351 p.

Briefly discusses thermal emissivities, atmospheric window problems and water vapor, and two instrument platforms (HCMR and AVHRR). Detailed discussion of AVHRR techniques is inapplicable to the characterization project since TM has only a single thermal-band window. Useful references.

Vukovich, Fred M. A preliminary study of the application of HCMM satellite data to define initial and boundary conditions for numerical models: a case study in St. Louis, Missouri. Research Triangle Park, NC: Geosciences Dept., Research Triangle Institute; March 1982; HFO-010. 109 pp.

Note: Prepared for NASA Goddard Space Flight Center.

Quite rigorous investigation, to all appearances; good discussion of mesoscale modeling factors, well referenced. Some characterizations of the surface for modeling purposes (particularly surface roughness; thermal inertias of simple rather than extremely complex, honeycombed surfaces) do not yet seem adequate for describing urban centers. For our purposes, this study primarily uses satellite thermal and albedo data as an adjunct to fairly extensive ground instrumentation. Vukovich reaches the same conclusion as Carlson (1981), viz. that a significant air-to-ground moisture flux can occur in urban centers even in daytime; this seems counterintuitive.

II. Data Acquisition and Problems Affecting Data Quality in the Urban Environment

Ackerman, Thomas P. A model of the effect of aerosols on urban climates with particular applications to the Los Angeles basin. *Journal of the atmospheric sciences;* 1977; **34:** 531-547.

A one-dimensional model that does include advective and other transport terms. Finds negative feedback in surface temperature responses: when near-surface (polluted) air absorbs, it is at the expense of the surface, which would have lost heat to the near-surface air anyway; other similar effects. However, the net result, increasingly evident with increasing concentrations, is energy denied to the system through shortwave backscatter. However, an important secondary effect is increased stability due to dampened surface heating resulting in reduced convection.

Ackerman, Thomas P; Liou, Kuo-Nan; Leovy, Conway B. Infrared radiative transfer in polluted atmospheres. Journal of applied meteorology; 1976; **15:** 28-35.

Multi-layered numerical model of scattering and absorbing aspects of aerosols finds that concentrations found in heavy pollution are capable of significant radiative cooling of atmospheric layers (since particulates especially are much more emissive than normal air), thus possibly contributing significantly to urban atmospheric stability and inversion reinforcement.

Atwater, Marshall A. Radiative effects of pollutants in the atmospheric boundary layer. *Journal of the atmospheric sciences;* 1971; **28:** 1367-1373.

Early inclusion of particulates in analysis of boundary-layer radiation budgets. Finds that the heating due to observed concentrations of particulates alone (in addition to effects of exotic gases) can exceed heating due to water vapor. Model predicts elevated inversions, i.e. inversions at altitude in the atmospheric column.

Atwater, Marshall A. The radiation budget for polluted layers of the urban environment. *Journal of applied meteorology;* 1971; **10:** 205-214.

Uses a numerical model to simulate thermal effects of concentrations of aerosols and nitrogen dioxide. Results indicate they may cause local radiative cooling, thus elevated in-atmosphere inversions. Believes their effects should be modeled in considerations of urban meteorology.

Bergstrom, R W Jr; Viskanta, R. Prediction of the solar radiant flux and heating rates in a polluted atmosphere. *Tellus;* 1973; **25:** 468-498.

Reports on a nonisotropic model test using exact parameterizations of pollution and other aerosol species. Finds that small concentrations of absorbing particles can significantly affect radiative transfer.

Brest, Christopher L; Goward, Samuel N. Deriving surface albedo from narrow band satellite data. *International journal of remote sensing;* 1987; **8:** 351-367.

A fairly thorough discussion of methods; MSS data are discussed exclusively here. Rigorous treatment of incoming solar spectral distribution; moderate treatment of per-band assumptions. Initial discussion (and thorough review) of albedo and anisotropy. Notes specifically that "No information regarding isotropy of two of the categories (city, suburb) discussed is known to the authors". Calculated urban-surface albedos ranged from about 3.5% (tar) to 46.4% (white enamelled aluminum).

Chavez, Pat S Jr. An improved dark-object subtraction technique for atmospheric scattering correction of multispectral data. *Remote sensing of environment;* 1988; **24:** 459-479.

This is the detailed discussion of Chavez's stand-alone radiometric calibration approach; for improvements, see Chavez 1989.

Chavez, Pat S Jr. Radiometric calibration of landsat thematic mapper multispectral images. *Photogrammetric engineering and remote sensing;* September 1989; **55**(9): 1285-1294.

The intent is to introduce simple methods of accurately estimating surface reflectance values from TM data, with or without ground truth in the form of measured sky brightness. Without ground truth, atmospheric attenuation is modeled across the TM bands starting with apparent brightness of dark objects in the image; this paper presents refinements of the approach described at length in Chavez (1988). The attempt with ground truth proved more accurate but still represents an improvement in simplicity: a multispectral radiometer was simply pointed vertically at the time of satellite imaging. Chavez has developed computer programs for these purposes.

Chen, T S; Ohring, George. On the relationship between clear-sky planetary and surface albedos. *Journal of the atmospheric sciences;* 1984; **41**(1): 156-158.

Finds the relation between true surface albedo and apparent albedo from above atmosphere is linear, given the latitude and solar zenith angle, under clear-sky conditions.

Crippen, Robert E. The regression intersection method of adjusting image data for band ratioing. *International journal of remote sensing;* 1987; **8**(2): 137-155.

A useful alternative to calibration with known atmospheres, data on sensor, etc; definitely more accurate for ratioing than dark-pixel subtraction approaches. Logic = given a homogeneous cover and some topography or inherent shadowing, a range of values will show up in the data, the brightness a function of illumination intensity only. Taking any two bands, the data in each band will exhibit a range of values but the values will differ between bands as a function of the reflectance of the particular cover in each band: plotting the bands against each other, a linear relation will be described. If two different homogeneous covers are treated in the same fashion, two linear relations will be described, and the intersection of their linear extensions must represent zero illumination, i.e. the absolute offset for atmospheric and sensor effects combined.

Hänel, Gottfried; Weidert, Detlev; Busen, Reinhold. Absorption of solar radiation in an urban

atmosphere. *Atmospheric environment;* 1990; **24B**(2): 283-292; ISSN: 0957-1272.

Important new methodologies. Indicates that solar extinction and atmospheric heating (up to 1.2° per day in study) may be more important than assumed. Study is rigorous, with new omnidirectional instrumentation; however, spectrum is not broken down.

Herman, Benjamin M; Browning, Samuel R. The effect of aerosols on the earth-atmosphere albedo. *Journal of the atmospheric sciences;* 1975; **32:** 1430-1445.

Model results indicate the effective albedo of the earth-atmosphere system always decreases under high aerosol concentrations if the surface albedo is above 0.4, whereas below this value the net result is a function of the particular aerosol constituents.

Holm, Ronald G; Moran, M Susan; Jackson, Ray D; Slater, Philip N. Surface reflectance factor retrieval from Thematic Mapper data. *Remote Sensing of Environment;* 1989; **27:** 47-57.

Took apart the TM data (in CCT "A" format) to recover the original radiance values, sensor-calibrated; ran these data through atmospheric correction, and compared with same-time aircraft data. This was performed for various large, uniform test plots on different dates. Agreement is excellent. Constitutes first real test of replicability of atmospheric correction algorithms for retrieval of equivalent data from different times and sources that represent true numeric reflectance values. Does not address adjacency, of course.

Isaacs, R G; Wang, W -C; Worsham, R D; Goldenberg, S. Multiple scattering LOWTRAN and FASCODE models. *Applied optics;* 1987; **26**(7): 1272-1281.

Reports on adding multiple-scattering code (as a separate step) to Fascode and Lowtran. At least somewhat successful; results are improved, especially Lowtran's estimates with long horizon paths.

***Kaufman, Yoram J. The atmospheric effect on the separability of field classes measured from satellites. *Remote sensing of environment;* 1985; **18:** 21-34.

This is a rigorous treatment of reflective and atmospheric optics. Merely points out the reduced of spectral analysis potential when adjacency effects are not accounted for in per-pix classification. Adjacency-effect correction algorithms should take care of this. The significance is that much per-pix classification is done on the assumption that ratioing takes care of atmospheric effects: in fact ratioing does not take care of adjacency effects, and that is the well-documented thrust of this paper.

Koepke, Peter. Removal of atmospheric effects from AVHRR albedos. *Journal of applied meteorology;* December 1989; **28**(12): 1341-1348.

Provides very rigorous linear coefficients for estimating absolute albedos using two channels of AVHRR data alone, assuming clear skies and for certain atmospheric conditions. Includes useful

discussion of the approach.

Lea, Duane A. Vertical ozone distribution in the lower troposphere near an urban pollution complex. *Journal of applied meteorology;* 1968; **7:** 252-267.

Found elevated strata of high ozone concentration, presumably L.A.-genic. Fits with the mountain slope inversion entrainment theory.

Liou, Kuo-Nan; Sasamori, Takashi. On the transfer of solar radiation in aerosol atmospheres. *Journal of the atmospheric sciences;* 1975; **32:** 2166-2177.

Model analysis predicts that albedos in the 0.3-0.4 range can have a significant impact on boundary-layer evolution under polluted conditions. Low albedos absorb enough of the decreased shortwave flux to continue heating the atmosphere from below, while higher albedos not only diminish surface heating but increase heating aloft, thus stabilizing rather than destabilizing the atmosphere (at ground level).

*Mateer, C L. Note on the effect of the weekly cycle of air pollution on solar radiation at Toronto. *International journal of air and water pollution;* 1961; **4:** 52-54.

Finds Sunday insolation over 20+ years is ~3% higher than weekday; effect may be lessening in late '50's.

Peterson, James T; Stoffel, Thomas L. Analysis of urban-rural solar radiation data from St. Louis, Missouri. *Journal of applied meteorology;* 1980; **19:** 275-283.

Incident all-wave solar radiation in and downwind of downtown St. Louis under cloudless conditions was decreased by ~4.5% in winter and ~2% in summer for urban sites, somewhat less for suburban and rural.

Richter, Rudolph. A fast atmospheric correction algorithm applied to Landsat TM images. *International journal of remote sensing;* 1990; **11**(1): 159-166.

Whether his algorithm is an extension to LOWTRAN-7 or a simplification of it isn't immediately clear. What he does offer is second-order atmospheric correction (band-dependent). First-order correction consists in removing the general scattering of light in the atmosphere (imagine you are trying to see an object through a fog bank with the sun behind you: much of the brightness you see is sun on fog; more of it is light from the landscape behind, including but not limited to the object, scattering on its way to you). Second-order correction consists in removing halo effects (after first-order correction, you can imagine your object acting like a neon sign beyond a fog bank at night: most of the fog isn't scattering much light at you, but the halo around the bright bits of your object obscures the dimmer bits; since the effect is radially symmetric it can be corrected for by subtracting an assumed halo from around each bit according to the bit's own brightness). Impressive looking results. Code evidently presented in Richter 1989.

Slater, Philip N; Biggar, Stuart F; Holm, Ronald G; Jackson, Ray D; Others. Absolute radiometric calibration of the Thematic Mapper. In: Slater, Philip N, ed. *Earth remote sensing using the Landsat Thematic Mapper and SPOT sensor systems;* 1986: 2-8. *(Proceedings SPIE;* v. 660).

Contains detailed tables of gains, correction factors etc for the Landsat-5 TM; uses pre-analyzed landscape at White Sands for comparison on several dates.

Slater, Philip N; Biggar, Stuart F; Holm, Ronald G; Jackson, Ray D. Reflectance- and radiance-based methods for the in-flight absolute calibration of multispectral sensors. *Remote sensing of environment;* 1987; **22:** 11-37.

Further analysis using White Sands data & Landsat 5 TM, review of results over time with Landsat 4 TM and CZCS, and introduction of simultaneous down-looking helicopter sensing for calibration.

Tanré, D; Herman, M; Deschamps, Pierre-Yves. Influence of the background contribution upon space measurements of ground reflectance. *Applied optics;* 1981; **20**(20): 3676-3684.

Finds that signal components due to scattering in the optical path of light from nearby objects is fairly easy to parameterize and correct for, given initial knowledge or assumptions about the aerosol content of the atmosphere.

Tanré, D; Deschamps, Pierre-Yves; Duhaut, P; Herman, M. Adjacency effect produced by the atmospheric scattering in Thematic Mapper data. *Journal of geophysical research. D, Atmospheres;* 1987; **92**(D10): 12000-12006.

After noting that small, deep bodies of water show different band characteristics than water far from land, realizes that since forward scattering is dominant in the atmosphere, water near land is "colored" by the nearby land, and in fact all pixels are affected by forward scattering from the surrounding region. Chromicity of light entering sensor is composed of (1) backscattered sun; (2) reflected direct sun from the ifov; (3) reflected indirect sun from the ifov; (4) reflected light (direct and indirect and 3rd generation) from adjacent region scattered into the ifov path; (5) reflected light (direct and indirect and 3rd generation) from adjacent region backscattered onto the ifov and reflected up.

*Uthe, Edward E; Russell, Philip B. Experimental study of the urban aerosol structure and its relation to urban climate modification. *Bulletin [American Meteorological Society];* 1974; **55:** 115-121.

Clearly demonstrates the superiority of lidar over acoustic sounder for atmospheric sounding. Also shows fascinating 24-hr time-lapse growth and degeneration cycle of the urban boundary layer as defined by aerosol mixing depths, with transient events.

*Wakimoto, Roger M; McElroy, James L. Lidar observations of elevated pollution layers over Los Angeles. *Journal of climate and applied meteorology;* 1986; **25:** 1583-1599.

Downward-looking lidar transects show clear echo traces of elevated pollution layers. They resemble seismic sounding traces more than anything else. They also trace upper-level circulation and other factors, and estimate orographic effects.

White, Warren H. The components of atmospheric light extinction: a survey of ground-level budgets. *Atmospheric environment;* 1990; **24**A(10): 2673-2679.

A useful review and reinterpretation of available studies across the U.S. Magnitudes of various effects, and differences in geographical and rural vs urban and seasonal studies are all examined. Examination of literature for U.S. seems quite complete. Some refs may be useful for identifying species of utility in near-surface vertical temp soundings.

Whitehead, D C; Lockyer, D R. Decomposing grass herbage as a source of ammonia in the atmosphere. Atmospheric environment; 1989; 23(8): 1867-1869.

Using controlled wind-tunnel environment meant to simulate yard conditions but with a closed atmosphere, found that clippings from highly-fertilized grass (2.98% nitrogen) released a significant fraction of their nitrogen as ammonia gas, whereas clippings of marginally-fertilized grass (0.92% nitrogen) released no detectable ammonia.

III. Classification and Analysis

Adams, John B; Smith, Milton O; Johnson, Paul E. Spectral mixture modeling: a new analysis of rock and soil types at the Viking Lander I site. *Journal of geophysical research. B;* 1986; **91**(B8): 8098-8112.

Uses factor analysis to create new bands: shadow, spectral reflectance, aeolian dust member, in-situ soil member, unweathered rock member. Thus winds up with image "maps" (image is a ground level oblique view from the Martian lander) of quasi-geologic members of the scene. Notes potential of method for other remote sensing analysis.

*Alexander, R H. Applications of Skylab data to land use and climatological analysis. Final report, Skylab/EREP investigation No. 469. Reston, VA: U.S. Geological Survey; 1976.

Attempted classification (USGS categories, see Anderson et al., 1976) of Boston vicinity from Skylab photographs; compared results with aerial photography results. Some error.

Anderson, John R; Hardy, Ernest E; Roach, John T; Witmer, Richard E. A land use and land cover classification system for use with remote sensor data; 1976. 28 p. (U.S. Geological Survey Professional Paper; v. 964).

System used by Pease et al 1980, and many others. Needs work, if it's to be used for urban energy budgets. Including everything from wet tundra to dry salt flats, the Level I category "Urban or Built-up Land" includes Level II classes as follows: Residential; Commercial and

Services; Industrial; Transportation, communications, and utilities; Industrial and commercial complexes; Mixed urban or built-up land; and, Other urban or built-up land. In practice, this is to be extended by the user according to project needs, but a completely fresh approach might be more useful, especially one that is defined by primitive topology.

Argialas, Demetre P; Harlow, Charles A. Computational image interpretation models: an overview and a perspective. *Photogrammetric engineering and remote sensing;* 1990; **56**(6): 871-886.

A thorough and incisive discussion of overall trends in computer analysis of image data, the challenges posed by increasing spatial and spectral resolutions, and the need for computer approaches to evolve toward the analytic algorithms of expert human interpreters. This article represents an important synthesis.

*Baraldi, Andrea; Parmiggiani, Flavio. Urban area classification by multispectral SPOT images. *IEEE Transactions on geoscience and remote sensing;* 1990; **28**(4): 674-680.

Classification means urban vs. rural, and the study aims at picking up the growth of the urban fringe. Some success with a "region-growing" technique.

Benediktsson, Jon A; Swain, Philip H; Ersoy, Okan K. Neural network approaches versus statistical methods in classification of multisource remote sensing data. *IEEE Transactions on geoscience and remote sensing;* 1990; **28**(4): 540-552.

This is an extension of neural-network analysis into multisource data (eg, scanner data with DEM, radar, previous mapping) and, importantly, includes reliability factoring which allows effective combination of different scales of data. Proves very effective but computationally demanding compared to classical per-pixel etc. analysis, though less so than other alternative algorithms. It is not clear whether this approach could incorporate contextual information.

Ellefsen, Richard (Dept of Geography, San Jose State University). Remote Sensing of Urban Terrain. Garbesi, Karina; Akbari, Hashem; Martien, Phil, eds. *Controlling summer heat islands. Proceedings of the workshop on saving energy and reducing atmospheric pollution by controlling summer heat islands;* Feb 23-24, 1989; Berkeley, CA: Energy Analysis Program, Applied Science Division, Lawrence Berkeley Laboratory; November 1989: 218-237. 351 p.

Discusses two topics: urban terrain zones, a fairly complete scheme for classifying urban subregions by structure types; and the "enviro-pod" oblique camera system for producing standard oblique shots of cities to allow studies of wall materials, rooflines etc. The classification scheme could well prove useful for characterization project purposes and certainly represents an improvement over the USGS classification scheme; concurrent classification by albedo and vegetative cover, at least, is also necessary.

*Forster, Bruce C. Principle and rotated component analysis of urban surface reflectances. *Photogrammetric engineering and remote sensing;* April 1985; **51**(4): 475-477.

Demonstrates use of rotation with principle component analysis to define an improved "greenness" or similar index.

*Gong, Peng; Howarth, Philip J. The use of structural information for improving land-cover classification accuracies at the rural-urban fringe. *Photogrammetric engineering and remote sensing;* January 1990; **56**(1): 67-73.

Classifies urban vs rural features by applying a Laplacian filter to pick out edge effects associated with urban-scale features (roads, roofs, yards, etc.) and then smooths the result to assign an "urbanness" index to image regions.

*Haack, Barry N. An analysis of Thematic Mapper simulator data for urban environments. *Remote sensing of environment;* 1983; **13:** 265-275.

Early test of NS-001 over Los Angeles. Hoping to use the better spectral and spatial resolution of TM (over MSS) to effectively run per-pix classification of urban terrain. In fact, finds intraclass variability a problem, especially in residential zones; this is exacerbated by the improved spatial resolution. Does not see problems with other classification, however.

*Jensen, John R. Spectral and textural features to classify elusive land cover at the urban fringe. *(The) professional geographer;* 1979; **31**(4): 400-409.

Reports on adding analysis of texture to traditional per-pix classification in attempting USGS Level II/III analysis of urban fringe TM data. Finds a marginal improvement. Nothing to write home about.

*Johnson, Douglas D; Howarth, Philip J. The effects of spatial resolution on land cover/land use theme extraction from airborne digital data. *Canadian journal of remote sensing;* 1987; **13**(2): 68-74.

Started with 2.5-m digital data, then merged it into 10-, 20- & 50-m resolutions. Found the obvious: higher res. allows recovery of smaller pure regions (eg. roofs); higher res. does nothing except improve edging on larger pure regions, eg. fields. Does not address tradeoff with classification re. multispectrally averaged cover type signatures (eg. roof/lawn/driveway/street of suburban at 80 m).

*Khorram, Siamak J; Brockhaus, John A; Cheshire, Heather M. Comparison of Landsat MSS and TM data for urban land-use classification. *IEEE Transactions on geoscience and remote sensing;* 1987; **GE-25**(2): 238-243.

Urban classes include heavy, medium, light urbanization only. Reports TM data helps in rural per-pixel classification but higher spatial resolution picks up heterogeneity in urban, causing confusion.

Lam, Nina Siu-Ngan. Description and measurement of Landsat TM images using fractals. *Photogrammetric engineering and remote sensing;* February 1990; **56**(2): 187-195; ISSN: 0099-1112.

Approaches single-band images as statistical surfaces, and analyzes them in terms of topological dimension (D) ... a number between 2 (a true plane) and 3 (a topologically closed 3-d object like a cube or sphere). Demonstrates some capability of distinguishing land covers by pattern of relative D values in different TM bands. Has possibilities.

*Leak, Stephen M; Venugopal, G. Thematic Mapper thermal infrared data in discriminating selected urban features. *International journal of remote sensing;* 1990; **11**(5): 841-857.

Reports on an experiment in adding thermal band data to automated land cover classification procedures using a supervised layered classification algorithm. While thermal data did improve results somewhat, results were still unacceptably poor, even for discriminating between the very broad categories used: three residential classes, railroads, two industrial classes, a "commercial/industrial fringe forest" class, and six non-structural classes. Underscores the inutility of traditional spectral-based classification for urban land use classification.

*Martin, Larry R G. Accuracy assessment of Landsat-based visual change detection methods applied to the rural-urban fringe. *Photogrammetric engineering and remote sensing;* 1989; **55**(2): 209-215.

The intent here is to build maps showing urban-to-rural change. Two approaches were tried: per-pix classification of scenes from different dates, and then comparisons of same; or per-pix classification of multitemporal data. Results seem moderately abysmal in either case, but the authors were less successful with the multitemporal classification attempt. The Toronto region, combining marked seasonality with ample moisture for short-term greening of virtually any disturbed surface, obviously presents particular problems for multitemporal analysis.

*Martin, Larry R G; Howarth, Philip J; Holder, Glenn H. Multispectral classification of land use at the rural-urban fringe using SPOT data. *Canadian journal of remote sensing;* 1988; **14**(2): 72.

Reports poor results using supervised and unsupervised classification of SPOT imagery; however, visual (hand) methods improve with SPOT as opposed to MSS data.

*Møller-Jensen, Lasse. Knowledge-based classification of an urban area using texture and context information in Landsat TM imagery. *Photogrammetric engineering and remote sensing;* 1990; **56**(6): 899-904.

Categorization of neighborhood units (defined by streets), demonstrating use of texture and other contextual data rather than per-pixel attributes; could be redefined for other purposes.

Satterwhite, Melvin B; Henley, J Ponder. Spectral characteristics of selected soils and vegetation in northern Nevada and their discrimination using band ratio techniques. *Remote sensing of environment;* 1987; **23**: 155-175.

The problem tackled is the analysis of vegetation under conditions of (1) sparse canopy, (2) arid-region phenotypics and (3) variable background (soils of contrasting types, also salts, debris, shadows). Of these, the most pertinent problem for urban vegetation analysis is the problem of poor "greenness" (eg NDVI signature) of water-stressed vegetation, and arid phenotypes specifically. "Greenness" gradients observed tended to reflect plant-available water gradients rather than plant biomass. The other similar urban problem is variable background, in the urban case due to the variety of artificial or disturbed surfaces.

Smith, Milton O; Ustin, Susan L; Adams, John B; Gillespie, Alan R. Vegetation in deserts: I. A regional measure of abundance from multispectral images. *Remote sensing of environment;* 1990; **31:** 1-26.

A working test of spectral mixture analysis working towards four categories: two vegetation spectra, two soil spectra, and a shadow class. Results look excellent. Question is whether urban areas can be addressed as simple enough spectral complexes. Pre-classification is a possibility.

Smith, Milton O; Ustin, Susan L; Adams, John B; Gillespie, Alan R. Vegetation in deserts: II. Environmental influences on regional abundance. *Remote sensing of environment;* 1990; **29:** 27-52.

See part I for methodology; these are the final results of the study. The weakest link is the precipitation.

Srinivasan, A; Richards, J A. Knowledge-based techniques for multi-source classification. *International journal of remote sensing;* 1990; **11**(3): 505-525.

This paper marks the first extension of "knowledge-based" or artificial-intelligence driven land cover classification into projects based on integration of data from different scanners or other sources. Of no immediate applicability to urban heat island studies since much necessary urban classification involves analysis of three-dimensional physical geometries.

*Toll, David L. An evaluation of simulated Thematic Mapper data and Landsat MSS data for discriminating suburban and regional land use and land cover. *Photogrammetric engineering and remote sensing;* 1984; **50**(12): 1713-1724.

Attempted USGS level 2 classification (in urban areas, this means: single family landscaped; single family nonlandscaped; multifamily dwellings; commercial/ industrial; construction) using NS-001 TMS data and MSS data. Added spectral bands improved classification. Higher spatial resolution degraded classification results due to single pixels of non-cover-specific characteristics of various kinds, in various covers.

Townshend, J R G; Justice, C O; Kalb, V. Characterization and classification of South American land cover types using satellite data. *International journal of remote sensing;* 1987; **8**(8): 1189-1207.

Proposal refers to this. It's a classical cover-category classification (at a continental scale) except that multitemporal data sets are used.

*Wharton, Stephen W. A spectral-knowledge-based approach for urban land-cover discrimination. *IEEE Transactions on geoscience and remote sensing;* 1987; **GE-25**(3): 272-282.

Achieves ~80% accuracy in distinguishing between 3 roof classes, 3 pavement classes, 2 tree classes, soil, grass, water and shadow, using NS-001 TM data at 5-m nadir resolution. This drops to 63% accuracy with 30-m TM data. Full discussion of spectral-knowledge-based approach.

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